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Arctic Tectonics and Volcanism: a multi-scale, multidisciplinary educational approach

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Abstract. Geologically, the Arctic is one of the least explored regions of Earth. Its significance, in terms of indigenous populations, resource extraction, tourism, shipping and a rapidly changing climate, is increasing. The Arctic offers geological diversity encompassing onshore and offshore environments, include active subduction zones in Alaska, deep sedimentary basins on the Siberian and Barents Sea shelves, widespread ancient Arctic volcanism and magmatism, the world's slowest spreading mid-ocean ridge (Gakkel Ridge in the Eurasia Basin), as well as world-class examples of extensional and compressional basins exposed onshore Svalbard. Obtaining data is logistically, economically and environmentally expensive ~~in the high Arctic~~, but the township of Longyearbyen at 78°N represents a relatively easily accessible gateway to Arctic geology. The year-round settlement on Spitsbergen, the main island of the Svalbard archipelago is home to The University Centre in Svalbard (UNIS). ~~Reached by a year-round airport with regular connections to mainland Norway~~, Svalbard provides a foundation from which to teach and explore Arctic geology via the classroom, the laboratory, and the field.

In this contribution, we present a new graduate course (Masters and PhD level) on Arctic Tectonics and Volcanism that we have established and taught annually at UNIS since 2018. We outline the course itself, before presenting student perspectives based on both an anonymous questionnaire (n = 27) and in-depth perceptions of four selected students. The course, with an intake of up to 20 MSc and PhD international students, is held over a 6-week period, typically in Spring or Autumn. The course

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comprises modules on field and polar safety, Svalbard/Barents Sea geology, wider Arctic geology, plate tectonics, mantle dynamics, geo- and thermochronology, and geochemistry of igneous systems. All modules include individual and group-based exercises in addition to introductory lectures. A field component, which in some years included an overnight expedition, provides an opportunity to appreciate Arctic geology and gather own field observations and data. Digital outcrop models and photospheres viewed with state-of-the-art visualization in the classroom facilitate efficient fieldwork through pre-fieldwork preparation and post-field work quantitative analyses. The course assessment is centered on an individual research project that is presented orally and in a short and impactful Geology journal-style article. Apart from the course at UNIS we have jointly initiated several one-off research and education-based events at partner institutions, and briefly outline these.

Key words: Arctic, education, field-based learning, multi-scale

1 Introduction

The Arctic is considered as one of the last geoscientific frontiers in the world. This is partly a function of the region being relatively poorly mapped (a result of access difficulties) and is compounded by the debate around its geological evolution. The centre of the Arctic is a deep oceanic basin, which is surrounded by shallower continental shelves of variable widths (Figure 1). The onshore domains are divided socio-politically into five coastal nations plus an additional three when considering nations north of the Arctic Circle (66°34'N) and is home to many indigenous peoples. The physiographic configuration underpins much of the climatic, oceanographic, biological and sociopolitical development of the region, both at present-day, recent past (100s – 100,000s years ago) to deep time (millions of years ago).

With warming from climate change occurring up to 4 times greater in the Arctic region due to polar amplification (Serreze and Barry, 2011), the region demands immediate attention and a concentration of efforts in order to prepare for the coming years, decades and beyond. It is inevitable that there will be increased human activity in the Arctic, ~~for example,~~ through a combination of natural resource extraction, tourism, shipping and fisheries. Global attention from the broader public is increasingly turning to the Arctic, and is reflected in both the media, governmental policies, and educational resources. An opportunity for geoscientists to contribute to this is through understanding and communicating the various driving forces that have created the features of the region, including how the region has undergone changes in the past, and how it will likely respond to various forcing factors in the future.

Characterizing the present-day Arctic Ocean and its surrounding submerged continental shelves relies on reconciling multi-physical data sets, including seismic reflection, seismic refraction, gravity, magnetic, bathymetric and sonobuoy data. Kristoffersen (2011) synthesizes the geophysical exploration of the Arctic Ocean, pointing to the challenges of thick sea ice during data acquisition and the necessity for Arctic-specific platforms like sub-ice submarines and drifting ice stations like the German-led MOSAiC icebreaker drift (Krumpen et al., 2021) or the hovercraft-based Fram-2014/15 (Kristoffersen et al., 2023) expeditions. In the past decade, exponentially more data were acquired. This was partly facilitated by diminishing sea ice, and partly by geopolitical considerations related to the United Nations Convention on the Law of the Seas (UNCLOS; Proelss, 2009). Through UNCLOS, the states geographically bordering the Arctic Ocean could apply to extend their continental shelf towards the central Arctic Ocean. Brekke and Banet (2020) outline the procedure from the Norwegian perspective, whose maritime territorial margins have been recently settled.

Understanding the geological evolution of the Arctic basin itself relies largely on deciphering the geology of the surrounding landmasses. Historically, a lot of Arctic research is conducted along N-S gradients – by Norwegians in Svalbard, Danes in Greenland, Swedes and Finns in northern Fennoscandia, Russians in Siberia, US in Alaska, and Canadians in Arctic Canada. The same could be said for the tertiary educational systems, where students often study in their country or continent of origin. However, such a latitudinal and unilateral framework limits a true systems-wide perspective and the basic and applied scientific discoveries that come with it. A circum-polar approach, with multi-national partners also from non-Arctic nations with significant Arctic research programmes (e.g., Germany, South Korea, China), is required. Furthermore, to understand the deep time evolution of this part of the world, and its place in the global system, a wide spread of geoscience disciplines needs to be

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integrated. Ideally, both research and educational projects should reflect this by spanning across both spatial and temporal scales.

A limiting factor to conducting research in the Arctic are the financial costs. This is particularly true for scientific field campaigns, whether conducted via land, sea, air or space. Universities and academic institutions (whether funded internally or via external funding agencies) thus take a deliberate and measured approach to acquire funding to support such activities. In addition to research, the role of education (here considering tertiary-level courses) and student mobility to and from ~~(~~and within~~)~~ the Arctic is crucial. The intersection of scientific research and education in the Arctic is thus an emerging opportunity.

Several pedagogical-meets-research approaches or activities have been recently implemented. For the geosciences, these include a high school classroom implementation of the Arctic Climate Connections curriculum (Gold et al., 2015), a special volume focussing on polar education (Gold et al., 2021) or insights into developing a field course in Arctic Geology (Malm, 2021).

The University Centre in Svalbard (UNIS; Figure 1) is a unique educational institution. It is a share-holding company, owned by the Norwegian Ministry of Education and Research and does not charge tuition fees. It was established in 1993 to provide university level education in Arctic studies, to carry out high quality research, and to contribute to the development of Svalbard as an international research platform. UNIS offers undergraduate, graduate and postgraduate-level courses, all delivered in the English language. One example of integration of research and education has been presented by Senger et al. (2021a) focussing on an annual BSc-level course taught at UNIS, “Integrated Geological Methods: from outcrop to geomodel”. The course has been partially externally funded through the University of the Arctic (UArctic) and paved the way for the development of the “Svalbox - digital outcrop model (DOM) database (Betlem et al., 2023; Senger et al., 2021b). Svalbox facilitates further activity including MSc and PhD projects that systematically contribute to the growing database of DOMs.

UNIS courses require a field component thus maximizing the benefit of being located in the natural laboratory of the high Arctic. With this in mind, no UNIS course could be physically run at universities

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on the Norwegian mainland, and UNIS is thus considered as Norway's field university. This is reflected amongst others in ongoing work as part of two Norwegian Centres for Excellent Education, BioCEED and iEarth, where UNIS is actively involved particularly with field teaching and learning. Some of this work reflects the increased use of digital tools such as digital field notebooks (Senger and Nordmo, 2021) or virtual field guides (Eidesen and Hjelle, 2023) to bridge the classroom to the field sites. Malm (2021) provides a more pedagogical approach focussing on a graduate course on Arctic Glaciers and Landscapes. Nonetheless, we currently miss a truly circum-Arctic approach that integrates the spatial and temporal range required to decipher the evolution of the Arctic region. Secondly, there are few publicly available thematic data sets that allow multi-disciplinary teaching of Arctic geology.

In this contribution we present an international collaboration project, 'NOR-R-AM' ("Changes at the Top of the World through Volcanism and Plate Tectonics"), described in more detail below. In particular, we focus on describing a direct outcome of this project, which was a 10 ECTS (European Credit Transfer and Accumulation System) MSc and PhD-level course jointly developed by project members. The 6-week course was held at UNIS and was titled "Arctic Tectonics and Volcanism". The annual course has run consecutively from ~~(including a 2-week pilot course)~~ ~~from~~ 2018 ~~onwards.~~ Throughout the course, integrating across temporal and spatial scales, across disciplines and across various software tools, are stressed as an important learning objective. In this paper, we also provide two quality-controlled data sets along with teaching material so that these datasets, and/or their formulations, can be implemented elsewhere, whether in Arctic, polar, geoscience or other courses.

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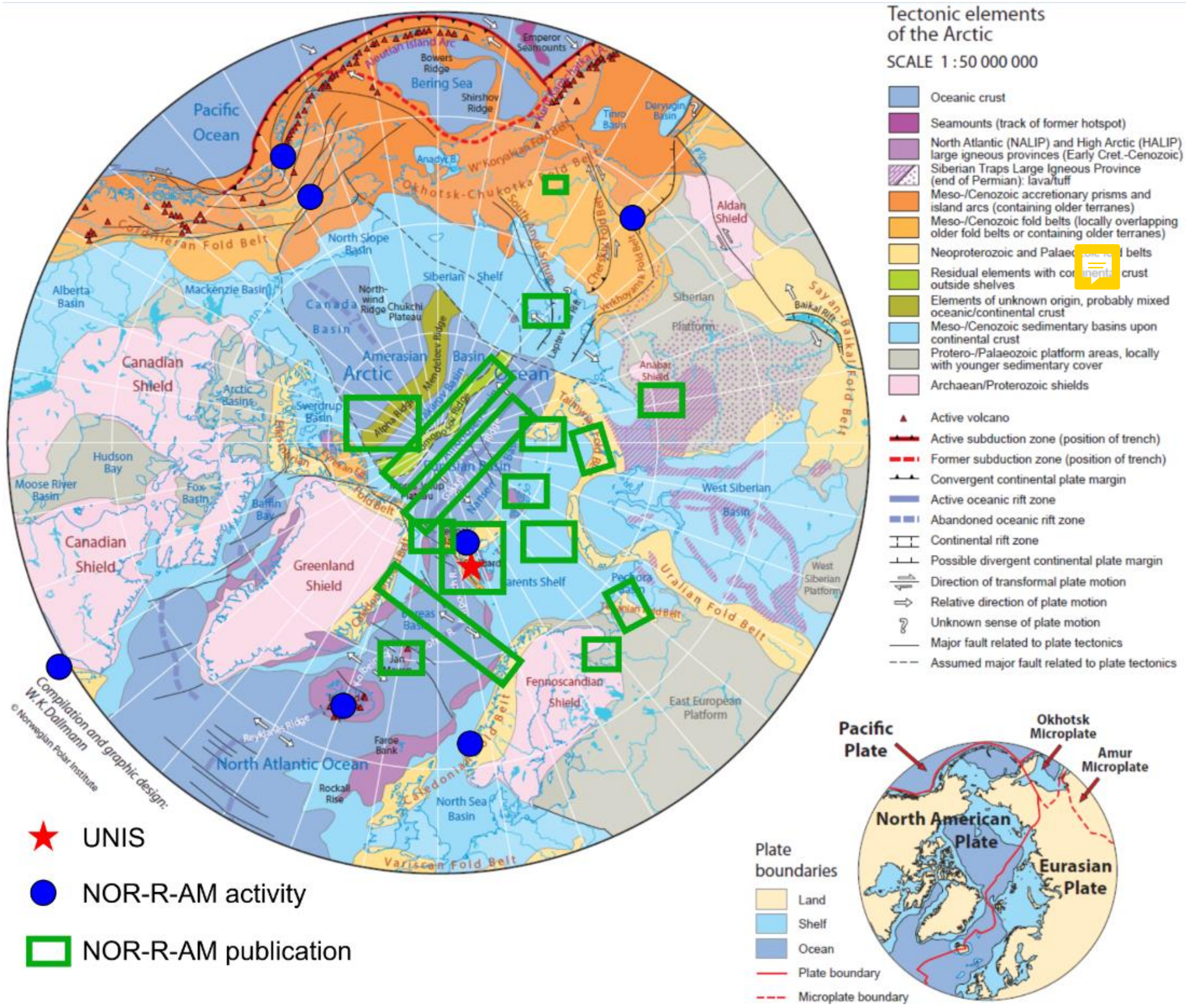

Figure 1: Tectonic elements map of Arctic. The red star marks the location of The University Centre in Svalbard (UNIS). Base map from Dallmann (2015). The blue circles indicate the location of NOR-R-AM activities as listed in Table 4. The green boxes indicate the approximate location of NOR-R-AM affiliated publications (Senger and Galland, 2022; Prokopiev et al., 2018; Prokopiev et al., 2019; Ershova et al., 2022; Rogov et al., 2023a; Rogov et al., 2017; Rogov et al., 2023b; Vasileva et al., 2022; Abdelmalak et al., 2023; Abdelmalak et al., 2024; Nikishin et al., 2018; Anfinson et al., 2022; Brustnitsyna et al., 2022; Ershova et al., 2018; Khudoley et al., 2019; Struijk et al., 2018; Døssing et al., 2020; Straume et al., 2020; Straume et al., 2022; Gaina, 2022; Blischke et al., 2022; Døssing et al., 2017; Kurapov et al., 2021; Lebedeva-Ivanova et al., 2019).

2 NOR-R-AM/NOR-R-AM2 project

NOR-R-AM is the acronym for the project "NOR-R-AM: *A Norwegian-Russian-North American collaboration in Arctic research and collaboration.*" There were two successive generations of the project, NOR-R-AM and NOR-R-AM2, which were funded for the period 2017-2019 and 2020-2023, respectively. ~~They were awarded under~~ the INTPART call (International Partnerships for Excellent Education, Research and Innovation) from the Norwegian Research Council

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(Norges forskningsråd) and SIU – The Norwegian Centre for International Cooperation in Education (now DIKU). T~~his~~ call for “Support and Mobility” was established to develop ~~more~~ world-leading academic environments in Norway ~~including by~~ enhancing the quality of higher education in Norway and ~~strengthening links of partnerships.~~ At the time of the call, partnerships for this call were possible with circum-Arctic nations USA, Canada and Russia. The two generations of the projects were led by Professor Carmen Gaina, from the Norwegian Centre of Excellence CEED (Centre for Earth Evolution and Dynamics, now Centre for Planetary Habitability), ~~and is a~~ collaboration with ~~other~~ world leading groups in Arctic geosciences~~.~~ ~~Partners~~ includ~~ed~~:

- University of Oslo, Norway
- University Centre in Svalbard (UNIS), Norway
- University of Alaska, Fairbanks (UAF), USA
- University of Texas (UTIG), USA
- Sonoma State University, USA
- Natural Resources Canada
- University of Ottawa, Canada
- Saint-Petersburg State University, Russia

The aim of the project was to set a scientific basis for deciphering the timing, driving forces and consequences of volcanism in the Arctic region. While educating the next generation of Arctic explorers, this international collaboration also prepared a scientific platform for future large, collaborative research initiatives in the Arctic. ~~To achieve this there were 6 Work Packages (WPs),~~ namely Onshore Geology (WP1), Offshore Geology (WP2), Arctic Seismicity and Deep Interior (WP3), Arctic volcanism and paleo-environment (WP4), Circum-Arctic Geodynamics (WP5), and Education (WP6)~~. E~~ach led by a partner institution. In this contribution we focus on WP6 Education, with emphasis on the course we jointly developed and taught at UNIS since 2018.

3 The AG-x51 course: motivation, establishment and incremental optimization

The “Arctic Tectonics and Volcanism” course (AG-x51) was a key deliverable of the NORRAM project and is offered at UNIS simultaneously as both MSc (course code AG-351) and PhD-level (AG-851) course. This course addresses the diverse geological history of the Arctic region, including both onshore and offshore regions from Paleozoic to recent times (over 500 Million years of history). This can be described as a 4-dimensional perspective because it looked at the surface, deep interior, present-day and deep past. The course focuses on the interplay of plate tectonics ~~(~~including rifting, seafloor-spreading, subduction and orogenesis ~~[mountain building processes]~~) and volcanism (including, arc, rifting and plume-related~~)~~ across several scales (Figure 2). It explores some of the outstanding questions ~~within the~~ Arctic research community with regional case studies, scientific datasets and state-of-the-art software programs and methodologies. Based in the gateway to the

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Arctic, Svalbard (Figure 1), the course is complemented by several field excursions which ~~examine~~ the well exposed outcrops and specifically the igneous rocks emplaced over large parts of the Svalbard archipelago.

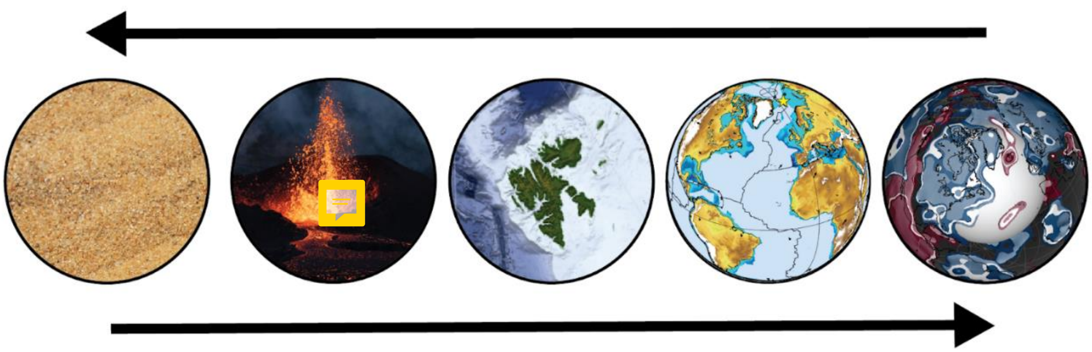

Figure 2: Synthesis of the Arctic Tectonics and Volcanism course, from rock samples to deep mantle processes. The course addresses heterogeneity laterally (Svalbard-Barents Shelf-Arctic-Depth-Global), in depth (shallow to deep processes) and across scales (from atoms and rock samples to global maps).

Entry requirements for this Masters and PhD course is the enrolment in a relevant Masters ~~and~~ PhD programme, respectively, anywhere in the world. A general background in structural geology, sedimentology, volcanology, geodynamics, or geophysics ~~was~~ encouraged, and previous geological field experience ~~was~~ advantageous, though not necessary. Many of the students who attended had little or no experience in Arctic geology, nor polar field work.

As with all higher education in Norway, the course has no tuition fee. Students ~~only~~ need to pay a semester fee (ca. 50 EUR) in order to sit all exams during a semester and contribute ca. 20 EUR per day towards food for overnight excursions.

The learning outcomes were designed to that, upon completing the course, the students will gain specific knowledge, skills and general competences:

Knowledge:

- understand the physical, chemical, and structural characteristics of volcanic provinces.
- be able to understand plate tectonic principles.
- be aware of the links between surface and deep mantle, methods and models using seismology and satellite data.
- understand the causal connections between tectonic evolution and episodic bursts of volcanism, as well as the impacts volcanism can have on the global climate.

Skills:

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- know how to identify first-order tectonic provinces from geophysical and geological data.
- be able to make a first order interpretation of geophysical, geochemical, and geological data connected to magmatic provinces.
- be able to make plate tectonic reconstructions using modern software.
- be able to interpret mantle tomography models and integrate them in large-scale tectonic interpretation.
- be able to identify and characterize igneous rocks in the field.
- be able to discuss how igneous plumbing systems may affect subsurface fluid migration.

General competences:

- gain first-hand experience of actively working both individually and in small groups.
- learn how to effectively and safely undertake field work in Arctic conditions.
- improve the presentation skills by presenting their work to their peers and creatively tackling the set problems.
- communicate their research findings through an article-style report.

4 The AG-x51 course: modules

Development and modification of the "Arctic Tectonics and Volcanism" course has continually occurred since beginning with a pilot course in 2018. The primary elements of this development can be broadly summarized as developments in the:

- overall course curriculum, in-line with UNIS and Norwegian University accreditation,
- the individual lectures by a large team of scientists from different career stages in academia and industry, which included theoretical and practical components,
- field work, including single day site visits and multi-day field trips involving multiple transport options (via sea and land, including using snow scooters). The locations visited were dependent on the time of year that the course was run (spring, summer, autumn), the availability of transport and logistics, cost, and finally, the weather and safety conditions on the day,
- outreach and science communication, with both the community in Svalbard and more widely.

These course components were largely spread across several topic-based modules which are described below in terms of major outstanding regional questions, key datasets and/or software as well as other considerations relevant.

4.1 Arctic geology and geophysics

Teaching about Circum-Arctic geology and geophysics in one ~~lecture~~ is a challenging task, although our student cohorts had a good geoscience background from their undergraduate studies. The challenge was to capture the most relevant and up to date information about this vast topic and to prepare the students for understanding other aspects of Arctic's structure and

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evolution during the rest of the course. In the first teaching year (2018), when the course was very short (10 days), the lecture presented, in a tour de force, what is known about the region's surface and sub-surface by reviewing latest knowledge and how it evolved in the recent time, of bathymetry and topography, geology and geophysics. A central role in this presentation was played by showing how an international Circum-Arctic mapping project gathered most of the updated information held by the Arctic nations (Norway, Russia, USA, Canada, Finland, Sweden, Denmark) for building geological, tectonic, and geophysical maps of the Arctic (Figure 3; Gaina et al., 2011; Petrov et al., 2021). The students learned that collecting geoscientific data in the Arctic is difficult and expensive, and wide collaboration with other countries and scientists is essential for advancing the knowledge of this remote region.

The lecture also emphasized the important role of remote sensing data, especially the satellite data, for deciphering the Arctic crustal and lithospheric structure. In addition, it presented the role of the upper and lower mantle and their heterogeneities in Arctic's tectonic and magmatic evolution and how mantle structures could be identified using tomographic models obtained from seismological data. As the course included field excursion in Svalbard, the lecture briefly mentioned how new geophysical data contributes to refined tectonic models of Svalbard and surrounding Barents Sea.

We slightly changed our pedagogy for subsequent years (2019, 2022 and 2023), when the course was offered for a longer period (6 weeks) and the students had more time to consult the recommended bibliography. The "Arctic Geology and Geophysics Overview" lecture built the understanding of this region by presenting the main tectonic features according to their ages, from oldest (cratons) to the youngest (oceanic basins). Relevant methods for assessing their structure and ages, with an emphasis on geophysical methods, were presented and when possible, examples including Svalbard and surrounding regions were given. We made sure that the geological connections between land and sea and among various Arctic sub-regions were presented in the regional ~~(and even)~~ global context, and that the latest published studies were included or mentioned in the presentation. The lecture was usually wrapped up by informing the future Arctic scientists about work in progress, the need for future studies and opportunities for student involvement in projects such as NOR-R-AM. Because there were several guest lecturers in attendance throughout the course, the students had the opportunity to discuss and ask more detailed questions about active research and outstanding questions.

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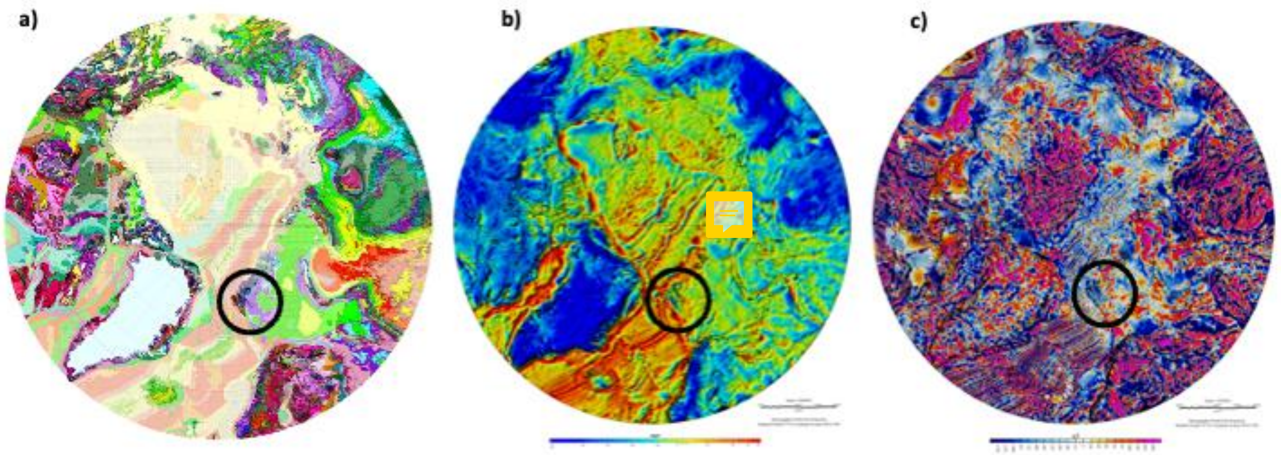

Figure 3: Maps showing the a) Geology (Harrison et al., 2008) and Geophysics (Gaina et al., 2011) as b) gravity anomaly and c) magnetic anomaly of the Circum-Arctic region. The black circle shows Svalbard and the surrounding area.

4.2 Arctic plate tectonics and mantle processes

Tectonics is a core theme of this course, and the various links between tectonic processes such as ~~ocean basin opening and closure~~, mountain building, ~~sedimentary basin formation~~, as well as magmatism ~~(including rift- and mantle plume related)~~. The link to climatic, oceanographic and biogeographic changes are mentioned throughout the lectures. Many of the students ~~will~~ have been introduced to the concept of plate tectonics, nonetheless, this module includes a set of introductions and more advanced lectures. Following on from a refresher about plate tectonics, including on a global scale, Arctic-specific tectonics were then delivered by dividing into three time-periods (which could be presented either running forwards or backwards in time) including the Cenozoic, Mesozoic and Paleozoic. These three time periods cover the major tectonic events including but not limited to North Atlantic and Eurasia Basin opening and Eurekan deformation (Cenozoic), Amerasia Basin opening and Pacific subduction (Mesozoic), and Ellesmerian deformation (Paleozoic). These events were discussed in terms of their influence on the regional to local tectonic expressions and influence on ~~sedimentation~~.

In addition to theory based lectures, several hands-on computer tutorials ~~showing~~ plate reconstructions were ~~undertaken~~ over 2-3 sessions. These tutorials are based on the widely used and open-source plate tectonics software GPlates (Müller et al., 2018; Boyden et al., 2011) which was installed either directly on the students' personal laptops or on the desktop machines in the lab. In addition to the default files ~~shipped~~ with GPlates, the students were provided with an Arctic dataset bundle (Senger and Shephard, 2023) which included vector and raster data specific to the Arctic and published in peer-reviewed articles by the wider Arctic community. The data includes regional gravity and magnetics and derivatives (Saltus et al.,

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2011; Gaina et al., 2011), crustal thickness maps (Lebedeva-Ivanova et al., 2019), seismic tomography models (Schaeffer and Lebedev, 2013; Ritsema et al., 2011) and bathymetry (Jakobsson et al., 2012). The students were ~~taught~~ about Euler and finite rotations, how to view and display plate reconstructions and related data including spreading rates and motion paths, how to change frames of reference (absolute and relative), import and export data and images, and make animations of tectonic motions through time.

Because plate tectonics is the surface manifestation of a convecting mantle, it is also relevant to explore the structure and evolution of the deeper Earth interior. It is also particularly relevant for the discussion of large-scale volcanism because their emplacement are often tied to the arrival of deep-seated mantle plumes that rise throughout the mantle and erupt at the surface. Such major volcanic and large igneous provinces of the Arctic include Iceland, the Paleogene North Atlantic Igneous Province (NAIP), the Cretaceous High Arctic LIP (HALIP) and the Permian Siberian Traps. In a set of at least two lectures the mantle is discussed ~~from a perspective of what are the major features (~~including subducted slabs ~~and~~ plumes and core-mantle boundary ~~features),~~ ~~what are the~~ main geophysical methods and datasets ~~(including~~ gravity and the geoid, seismic tomography and numerical modelling and geochemistry~~)~~, and what the potential role of mantle dynamics are in the enigmatic origins of the long-lived and pulsed HALIP. ~~As part of this lecture,~~ the community-based visualization website SubMachine (Hosseini et al., 2018) ~~was shown to the students, who learned how~~ to plot and analyse different tomography models, both globally and specifically for the Arctic region.

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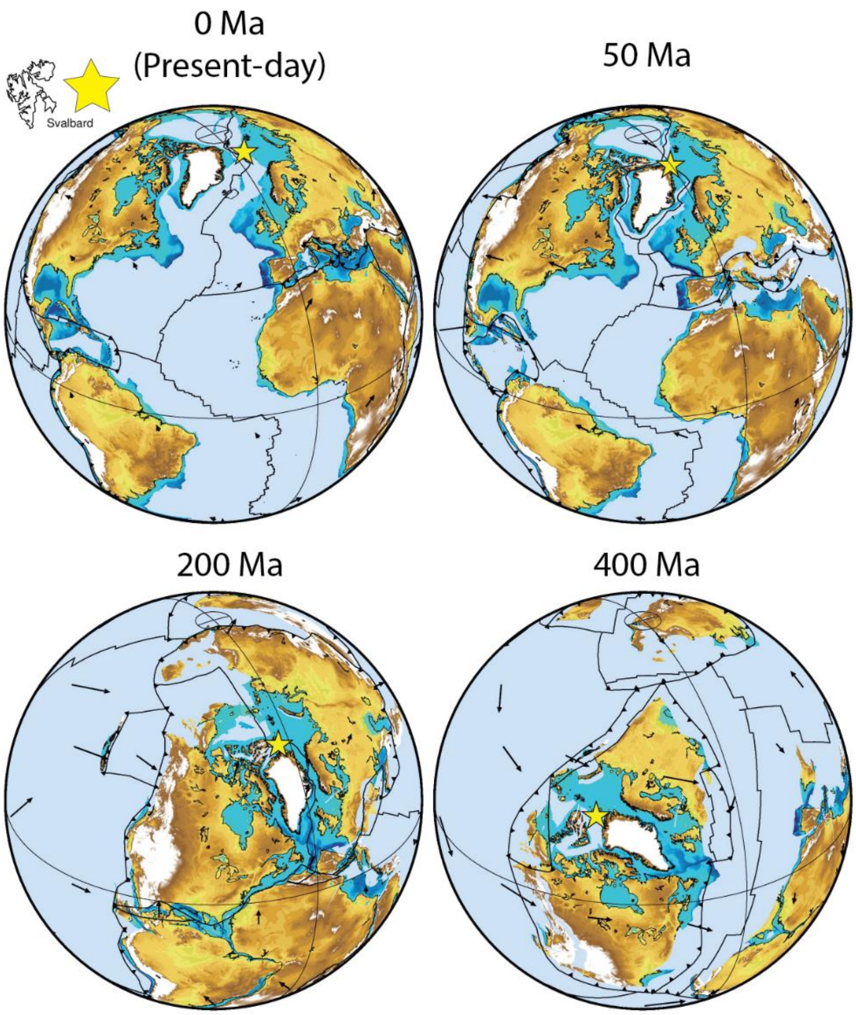

Figure 4: Plate tectonic reconstruction of Svalbard (located at yellow star) and the Arctic in the global tectonic setting at present-day (0 Million years - Ma), 50 Ma (opening of the Eurasia Basin and North Atlantic), 200 Ma (pre-opening Amerasia Basin), and 400 Ma (Arctic located in equatorial latitudes). Based on the global plate reconstruction of Müller et al. (2018) constructed from regional studies, made using the GPlates software. Present-day topography and bathymetry (cut to continental domains, light blue in oceans) for reference only.

4.3 Regional geology with Arctic and Barents Shelf connections

Svalbard plays a critical role in our understanding of the tectonic and paleogeographic evolution of the Arctic. In this section of the course we explore the regional geologic setting of Svalbard and delve into the tectonic events that have shaped Svalbard by placing those tectonic events into the larger tectonic evolution of the Circum Arctic. This begins by introducing the students to the major continental blocks that surround the present day Arctic (i.e. Baltica, Laurentia, and Siberia; Figure 5A) and introducing them to some of the currently exposed continental fragments within the Arctic (e.g. Svalbard, Franz

Joseph Land, New Siberian Islands, Wrangel Island) that lend insight into the overall tectonic and paleogeographic framework of the Arctic (e.g., Blakey, 2021). We then focus on the Neoproterozoic and younger mountain building events (e.g., Timanidan Caledonian, Ellesmerian/Svalbardian, Uralian, and Eurekan mountain belts) that have either influenced the tectonic structure of Svalbard, or have been a major sedimentary source for sedimentary successions exposed in Svalbard. This section of the course culminates with a focus on detrital zircon geochronologic data sets that have been collected from Paleozoic sedimentary strata across the Arctic, and how data collected (as part of this course) from Svalbard has aided our understanding of Svalbard's regional tectonic evolution (Anfinson et al., 2022; Figure 5).

To the south and east, Svalbard is directly connected to the submerged parts of the Barents Shelf (Figure 5). Geoscientists involved in ongoing petroleum exploration and production, as well as active CO_2 storage, in the south-western Barents Shelf use Svalbard as an excellent analogue to the reservoirs and cap rocks further south (Olaussen et al., 2024; Henriksen et al., 2011). The region is naturally rich in exploration well and seismic data, with a much denser coverage than onshore Svalbard. These data are not only used to constrain the reservoir extent and architecture, but also understand the larger-scale trends. Notable examples include detailed characterization of major sedimentary wedges in the Triassic and Cretaceous. The Triassic system, representing the largest delta plain in Earth's history (Klausen et al., 2019) is a westerly prograding system seen as clinoforms in seismic data across the Barents Shelf (Glørstad-Clark et al., 2011; Gilmullina et al., 2021) and as sand-prone sediments onshore Svalbard (Anell et al., 2014; Lundschien et al., 2014). The Cretaceous system is linked to uplift to the north associated with HALIP emplacement, regional tilting and a fluvial-dominated system traversing Svalbard from the north depositing sediments to the south (Midtkandal et al., 2019; Grundvåg et al., 2017).

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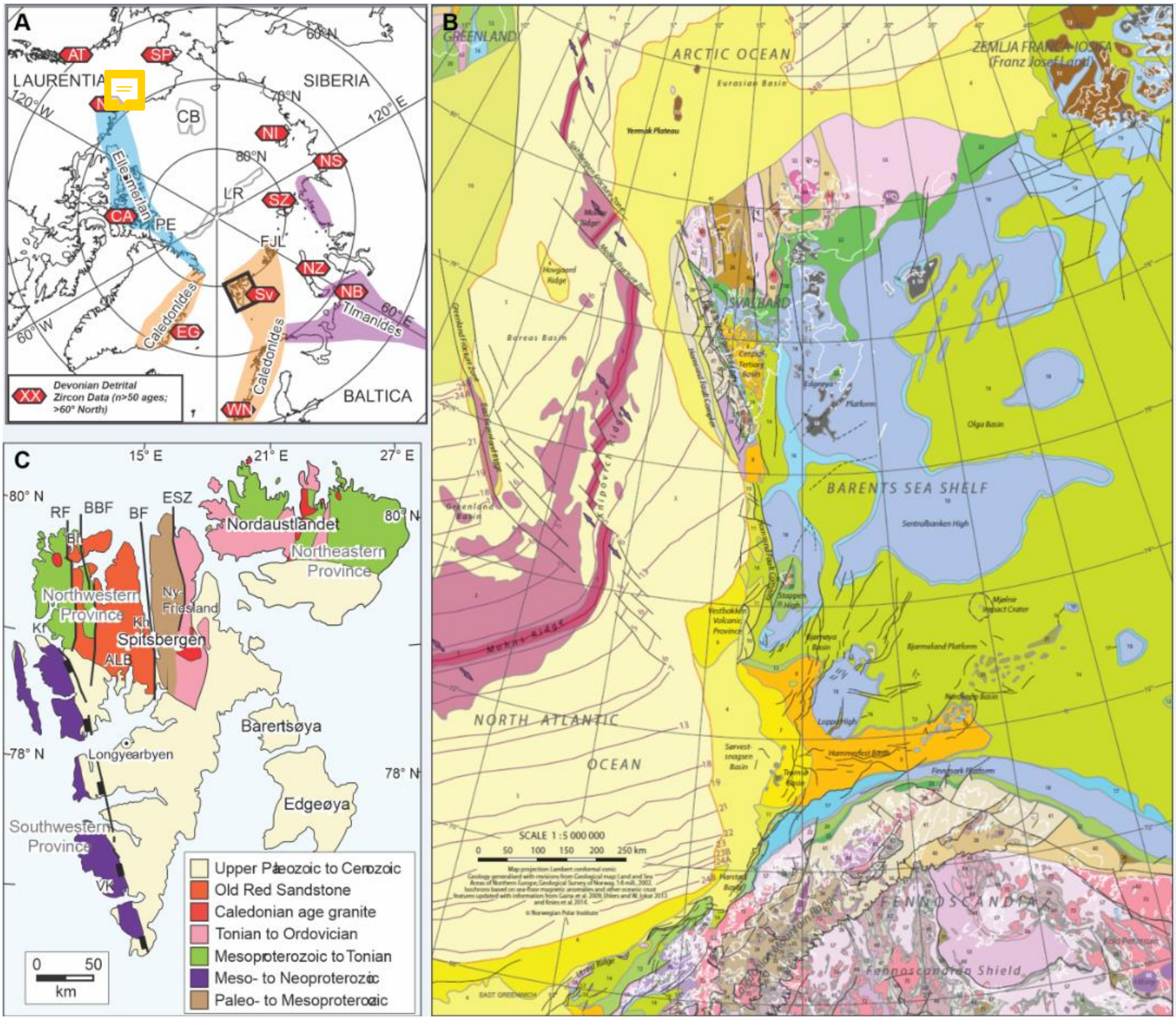

Figure 5: A) Schematic tectonic map of the modern Arctic depicting the general location of the Timanian, Caledonian, and Ellesmerian mountain belts. Symbols indicate the location of Devonian detrital zircon data (see Anfinson et al. (2022); map adapted from Colpron and Nelson (2009). Detrital Zircon Locations: EG, East Greenland; CA, Canadian Arctic Islands;, NC, Northwest Canada; AT, Alexander terrane; SP, Seward Peninsula; NI, New Siberian Islands; NS, Northeast Siberia; SZ, Severnaya Zemlya; NZ, Novaya Zemlya); NB, Northern Baltica; Sv, Svalbard; WN, Western Norway. Geographic references: PE, Pearya terrane; LR, Lomonosov Ridge; CB, Chukchi Borderland; and FJL, Franz Joseph Land. B) Setting of Svalbard on the interface between the North Atlantic and Arctic Oceans and the rest of the Barents Shelf, figure from Dallmann (2015). C) Geologic terrane map of Svalbard showing the location of the Northeastern, Northwestern, and Southwestern provinces. Tectonic elements: Billefjorden Fault Zone (BFZ), Breibogen Fault (BBF), Raudfjorden Fault (RF), Eolussletta Shear Zone (ESZ), the Vimsodden-Kosibapasset shear zone (VK), and the Andre Land Basin (ALB). Geographic references: Kh- Kronprinshoegda; Kf-Kongsfjorden; Bh- Biscayarhalvoya. Map adapted from Beranek et al. (2020) and based on the geologic map of Gee (2015).

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4.4 Svalbard geology, digital geology and data mining

The Svalbard archipelago, with its Polar climate, offers vegetation-free, well-exposed outcrops testifying a diverse tectono-stratigraphic evolution of the region. Geologically, Svalbard is presently the emergent part of the Barents Shelf but has pre-Eurekan been linked to Arctic Canada and northern Greenland. The nearly continuous stratigraphic record from the Devonian to the Paleogene (Olaussen et al., 2024) provides evidence of Svalbard's northward drift through time, overprinted by changing tectono-stratigraphic configurations. These include mid-Carboniferous rifting, Permian platform carbonates, Mesozoic siliciclastic deposits intruded by an igneous complex and a Cenozoic fold-and-thrust-belt with an associated foreland basin. Late Cenozoic sediments are not present onshore Svalbard but occur in depocentres along the northern and western shelf margins off Svalbard.

However, Svalbard's high Arctic position means that the rocks are snow-free and accessible only during a short summer season, typically from June to mid-September. During these times boat-based transport and hiking is possible. Conversely, snow cover provides relatively easy access to large-scale inland outcrops (that are too difficult to reach by foot) during the winter season with adequate light, from March to early May. The high seasonal dependence, combined with sudden weather events, has motivated us at UNIS to systematically acquire and openly share digital outcrop models (DOMs) and photospheres through the Svalbox database (Betlem et al., 2023; Senger et al., 2021b). These DOMs are georeferenced high-resolution 3D representations of the outcrops and facilitate quantitative sedimentological and structural work. Through Svalbox the DOMs are also put in a regional context through spatial integration of maps (geological, topographical, paleogeographic, geophysical etc.), surface (digital terrain models, satellite imagery etc.) and subsurface (boreholes, geophysical profiles, published cross-sections etc.) data, as illustrated for the Festningen geotope by Senger et al. (2022). Photospheres are systematically acquired as part of regular Svalbox campaigns and thematically grouped in virtual field trips using the VRSvalbard.com platform (Horota et al., 2024). These drone-based 360° photographs provide a bird's eye perspective of the visited sites and are complementary to the more quantitative DOMs. Photospheres are also integrated in thematic data sets, for instance related to the West Spitsbergen Fold-and-Thrust belt (Horota et al., 2023) visited during the October 2022 field campaign, to facilitate data access and the development of student projects. Students actively use these digital resources in the course both to prepare for field work and to conduct quantitative analyses as part of their individual research projects (Figure 6).

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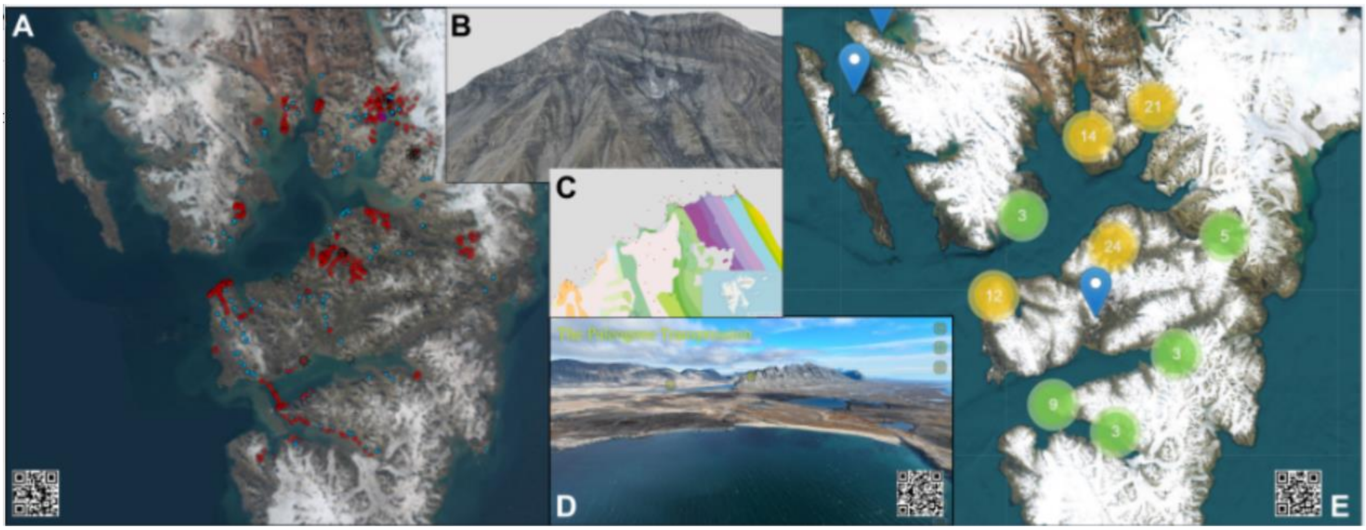

Figure 6: Synthesis of key digital tools made available to the students. A) Svalbox map (www.svalbox.no/map) interface with digital outcrop models (blue dots) and photospheres (red dots). B) Example of a digital outcrop model of compressional tectonics at Lagmannstoppen (Lord et al., 2021). The model was used as a basis of a research project in 2023. C) Zoom-in of the Svalbox map interface across the famous geotype profile at Festningen. The geological layer is now used as a base map. D) Thematic virtual field trip of the Paleogene transpression that has amongst others tilted the layers at Festningen. The field trip is related to a thematic data set used in the course (Horota et al., 2023). E) Overview of photosphere coverage in the VRSvalbard platform (www.vrsvalbard.com/map; Horota et al., in review), including photospheres specifically targeting the AG-x51 course.

4.5 Geochronology and thermochronology

Providing constraints on the absolute timing and duration of deformation and magmatic, metamorphic, or stratigraphic processes is of critical importance for deciphering the plate tectonic evolution of the Arctic. Radiometric dates serve as both input parameters and/or testable benchmarks for tectonic and thermal processes on all scales, ranging from plate tectonic reconstructions, timing of magmatism, or basin burial and maturation. The geochronology and thermochronology component of the AG-x51 course consists of three different learning modules: 1) overview and theory of radiometric dating methods, 2) application to tectonic and magmatic processes in the Arctic, and 3) hands-on exercises in detrital zircon U-Pb provenance analysis. The overview and theory for the geochronology portion covered the basics of radioactive decay including which long-lived isotopes undergo radioactive decay and are commonly used in earth science applications, half-lives, how we can use the measured daughter and parent isotope ratios to calculate an age, and what makes a good mineral or system to use (i.e., radioactive parent with well-defined half-life, no non-radiometric daughter isotope at t=0, mineralogic stability, etc.). We then focused on U-Pb geochronology, which is widely applied everywhere including the Arctic, and how we measure, calculate, plot and evaluate U-Pb ages. We discussed how U-Pb chronology can be applied to a wide suite of Arctic questions with specific examples including dating HALIP around the Arctic (Evenchick et al., 2015; Corfu et al., 2013) and paleogeographic reconstructions using detrital zircon U-Pb provenance (Anfinson et al., 2012). The thermochronology portion introduced thermally activated diffusion and closure temperature (Dodson, 1973) as they apply to noble gas thermochronology (i.e., Ar-Ar and (U-Th)/He systems), and the basic principles of fission track thermochronology. We discussed the differences in geo- and thermochronology, and then the power or combining different methods to understand thermal and tectonic histories and discussed an example of using 40Ar/39Ar thermochronology to understand Eurekan deformation on Svalbard (Schneider et al., 2019). The students were then introduced to geochron.org, a public database for geo- and thermochronology data, and did various searches for data so they learned resources to acquire and use available geochronologic data in their own projects.

4.6 Volcanism and paleoenvironmental implications

The climatic impacts observed from historical volcanic eruptions are well documented, which allows us to assess the possible effects of elevated magmatic activity in the geological record. Global climate is both dynamic and complex, and there is a plethora of ways that volcanic activity can influence local, regional, and global environmental conditions. This section of the course begins with an introduction to volcanism and magmatic systems, covering how melts are produced and how factors such as depth and degree of partial melting affect the melt composition. We then focus on the primary constituents of the melt, and how this affects the physical properties of the magma such as viscosity and saturation of volatile phases. We then follow the magmatic plumbing system towards the surface and investigate how these factors drive the style and explosivity of eruptions with the aid of a practical class. We end this section of the course by applying this information to outcrops in Svalbard, including the ash layers in the Paleocene Firkanten Formation around Longyearbyen and also in Permian-Triassic sediments at Festningen. These layers act as marker horizons, which are used to help constrain plate reconstructions in the Arctic (Jones et al., 2017).

Once an understanding of volcanic processes has been established, we introduce the concepts of regional and global climate. This includes concepts such as the greenhouse effect and how changes in atmospheric concentrations of greenhouse gasses affect the climate through time. We then take this information based on current observations into the paleoclimate realm, covering what methods of proxy data are used to estimate paleoenvironmental conditions, and at what timescales each of these proxies can be used. Once these key ideas are established, we focus on volcanism and how elevated activity can perturb the climate system. This includes emissions of climate-sensitive gasses such as sulfur and carbon species, and how different sources (e.g., volcanic degassing vs. emissions from contact metamorphism around shallow intrusions) have differing climatic impacts. We also consider post-eruption processes, such as the silicate weathering of volcanic ash as a significant atmospheric carbon sink. This section of the course is concluded by investigating examples of large scale volcanic activity and environmental disturbances in the geological record in Svalbard, including the North Atlantic Igneous Province coeval with the Paleocene-Eocene Thermal Maximum, and the Siberian Traps being emplaced at the same time as the end-Permian mass extinction.

The role of contact metamorphism in Large Igneous Provinces (LIPs) is manifold and is directly relevant for the Svalbard archipelago. One of the most important effects of LIPs is the thermal impact of magma on the host rocks. The associated thermal maturation and/or cracking of organic matter found in sedimentary host-rocks not only impacts hydrocarbon resources but also was responsible for releasing massive quantities of greenhouse gasses in the Earth's past resulting in multiple mass extinction events (Svensen et al., 2004; Wignall, 2001; Hesselbo et al., 2002). Numerical modeling of these processes is an important tool to understand the effects they have on the environment and to also better constrain the physical parameters that drive them.

The course introduces the general physical processes and the associated equations that occur during magmatic emplacement. Basic modeling concepts, its advantages, uses and caveats are outlined. A practical course that walks the students through the modeling of sill complexes with global examples and data from various LIPs is carried out using Silli1D (Iyer et al., 2018), with specific focus on HALIP magmatism in Svalbard (Brekke et al., 2014; Senger et al., 2014a). Silli1D is an open-source, 1D FEM modeling tool that is specifically tailored to study the thermal effects of sill intrusions on the surrounding host-rock. Model input is provided using MS Excel worksheets, which makes it accessible to a large audience with no previous programming skills. Input data is provided in the form of a simplified present-day well log or outcropping sedimentary column and includes relevant rock parameters such as thermal conductivity, total organic carbon (TOC) content, porosity and latent heats. Multiple sills can be emplaced within the system with varying ages and temperatures. Besides sill processes, the model also includes sedimentation and erosion, if any, to account for realistic basin evolution. The model output includes the thermal evolution of the sedimentary column through time and the host-rock changes that take place following sill emplacement such as TOC changes, thermal maturity (vitrinite reflectance) and the amount of organic and carbonate-derived CO_2. Rock parameters such as thermal conductivity and porosity are uncertain but only play a secondary role in controlling the overall thermal effects in a sill complex. The relative timing of sill emplacement together with emplacement temperature, however, exert first-order thermal control in the aureole around a sill complex. These parameters are also not well constrained. The Silli models can be used to better constrain such parameters if calibration data such as vitrinite reflectance is available by minimizing the error of the modeled results to the data. The amount of erosion also affects the background thermal maturity and can also be better estimated, similar to sill emplacement parameters, by comparing the modeled maturity to the data. A number of examples are worked through with the students with a few examples set aside as supervised exercises. The students are also encouraged to use the tool to investigate sill-complex outcrops from the HALIP.

4.7 Field Safety

Safe field operations are paramount and compulsory safety courses are held for all students and guest lecturers participating in the field component of the course. Usually these safety lectures and courses cover two full working days. One day is spent on safe rifle handling and polar bear encounter prevention, ending the day with a practical shooting exercise at the rifle range outside Longyearbyen. The second day involves season-specific training, either survival suit/small boat operations (for fieldwork in summer/autumn) or snowmobile safety and driving (for fieldwork in spring). During the fieldwork, plans were adapted to account for weather conditions and wildlife sightings. As an example, the Paleogene basin infill sequence was only investigated from a distance, aboard the M/S Polarsyssel, in October 2023 due to a polar bear sighting in the area (Figure 8D).

4.8 Fieldwork

Field work is an integral part of all UNIS courses and also this course is designed around the field component (Table 1; Figure 7). Due to the changing seasons at which time the course was held we have had to adapt to changing environmental conditions and logistical requirements and options. Nonetheless, the field work always tied the broader Barents Shelf and Arctic Geology evolution to outcropping units that the students were describing and discussing as part of their field tasks. The Festningen profile, Svalbard's only geotope (i.e. an area formally protected because of geology), was visited both in late summer and early spring (where we experienced a 0.5 m snowfall in the month of May). At Festningen, the students were able to visit and describe the main stratigraphic intervals and discuss correlations to the Barents Shelf and other Arctic basins. The entire section has been digitalized as a high-resolution DOM and integrated with geoscientific surface and subsurface data (Senger et al., 2022), which the students actively use in both preparing field stop preparations and post-field work analyses.

Another key target for the field campaigns are the exposures of the Diabasodden Suite (Senger et al., 2014b; Dallmann et al., 1999), the local equivalents of the Early Cretaceous HALIP. The dolerites are exposed throughout Svalbard and we often targeted the excellent exposures at Botneheia and Grønsteinfjellet. Here both sills and dykes are well exposed, and intersect a potential CO_2 storage reservoir-cap rock system. This provides a theme for discussing how igneous plumbing systems affect subsurface fluid flow and also how the Svalbard dolerites correlate to the circum-Arctic HALIP.

Depending on the season and transport options we also visit sites of relevance for tectono-stratigraphic evolution. These include the West Spitsbergen Fold-and-Thrust belt (the Svalbard part of the Eurekan mountain building event affecting large parts of the Arctic; Braathen et al., 1999; Piepjohn et al., 2016) and the associated foreland basin, the Central Spitsbergen Basin (Helland-Hansen and Grundvåg, 2020) as well as the mid-Carboniferous rift basin at Billefjorden (Smyrak-Sikora et al., 2019). Key sites that cannot be visited in person are addressed in lectures and using digital outcrop models and virtual field guides including the WSFTB thematic data package provided by Horota et al. (2023).

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Figure 7: Snapshots from the field component of the course. A) Investigating a HALIP igneous intrusion from a small boat and walking at Tshermakfjellet in July 2019. B) Investigation of the Early Cretaceous Helvetiafjellet Formation at Festningen, Oct 2022. The Polarsyssel boat used as a base is in the background. C) Fieldwork at the Festningen profile, late April 2023. D) Polar bear seen through binoculars aboard the Polarsyssel, Van Keulefjorden, Oct 2022. E) Clinoforms in the infill sediments of the Central Spitsbergen Basin, as seen from Reindalen, late April 2023. F) Scooter-based excursion to Isfjord Radio, late April 2023. Thrust tectonics related to the West Spitsbergen Fold-and-thrust belt are seen on the Vardeborgsfjellet mountain in the background. G) Investigation of the lower contact between a HALIP dolerite intrusion and Permian carbonate-dominated host rocks at Blomesletta, October 2023. Note the survival suits used for safe access to this beach-side locality.

Table 1: Summary of field activities undertaken as part of the course. LYR = Longyearbyen

Field period	Locations	Platform
August 2018 (pilot course)	Diabasodden	Day trips from LYR
June-July 2019	Tschermakfjellet, Diabasodden, Endalen	Day trips from LYR
2020-2021	no course due to Covid-19 restrictions	
Oct 2022	Diabasodden, Grønsteinfjellet, Van Keulenfjorden, Ekmanfjorden, Billefjorden	Day trip from LYR 4 day overnight excursion aboard Polarsyssel
April-May-June 2023	Botneheia, Festningen, Reindalen	Snowmobile trips. Both day trips and 3-day overnight trip with base at Isfjord Radio

5 The AG-x51 course: assessment

All students must complete and pass the assessments to pass the course and receive the 10 ECTS credits. The assessment was broken into three components for the PhD-level students and two for the Masters students.

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1. A pre-course assignment which comprised an oral presentation of a scientific peer-reviewed paper which was presented to the class in the first weeks. The students could choose which paper to present from a set list provided before the start of the course. This presentation was worth 20% of the final grade for the PhD students (0% for the Masters students).
2. An oral presentation of a small research project in the final week of the class that had been developed throughout the course. This presentation was worth 20% of the final grade for all students. The idea was that the students would be exposed to a range of Arctic geology topics, datasets and software and would choose their proposed topic within the first 2 weeks, with ongoing guidance from someone from the lecturer team throughout the course. The students were encouraged not to simply choose a topic they may already be familiar with (or that formed their existing Masters of PhD-level thesis), but to use this opportunity to learn new skills and knowledge.
3. A "Geology" journal-style paper (4 pages including figures, tables, references) which was handed in around two weeks after the course had concluded. This paper would be based on the research project presented in point 2 and was worth 60% of the final grade for PhD students and 80% for Masters students.

Final grades were a letter grade from A (excellent) to F (fail) and delivered ca. 1 month after the end of the course. For the oral presentation of the projects, the students were given peer-evaluation forms to help provide constructive feedback to each other.

The research projects, with titles listed in Table 2, reflect the broadness of the course and also the student's own research interest. Numerous project ideas with associated data sets were made available, but students could also develop their own project ideas. Some of the projects, for instance contact metamorphism studies using Silli or plate tectonic reconstructions using GPlates, were directly tied to one of the course modules. Weekly update meetings were conducted with the students to ensure smooth progress. However, a lot of individual responsibility for time management was also strived to reflect the challenges of authentic life geologists will experience in future careers, be it in academia or the private sector.

Table 2: Titles of student research projects conducted over the years, and the diverse geographic background of the students. 15 students participated in the pilot course in 2018 but no individual assessment was conducted in the short course.

2019 (13 students)	**2022 (15 students)**	**2023 (14 students)**
Students from institutions in Norway, Russia, Netherlands, Sweden, Germany, USA and Austria	Students from institutions in Norway, Netherlands, Estonia, Finland, Canada, Germany, USA and Austria	Students from institutions in Norway, Denmark, Sweden, Finland, USA, Germany, Switzerland, Austria and Netherlands
Paleogeographic reconstruction of the	Linking tomography anomalies to Arctic	Early Cretaceous High Arctic LIP

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Amerasian Basin during the Mesozoic through geophysical observations	subduction: voting for the best candidate	timing with anoxic events
Exploring the possibility of a common mantle link between the Iceland Plume, the High Arctic Large Igneous Province, and the Siberian Traps	Assessing the use of fracture orientations in sills as a proxy for sill geometry: An example from the Diabasodden Suite of Svalbard	Heat flow modelling for geothermal potential of Longyearbyen, Svalbard
Structural analysis of the Old Red Sandstone Munindalen outcrop (Dickson Land, Svalbard)	A large-scale Virtual Outcrop Model geometrical analysis of igneous intrusions: A central Spitsbergen example.	Modelling Svalbard sill intrusions and resulting greenhouse gas emission from contact metamorphism
Quantifying fracture networks in doleritic sills from Diabasodden, Svalbard	Satellite and airborne geophysical potential anomalous expressions of the crustal structure in Svalbard	Mapping of Igneous Intrusions using Onshore Magnetic Data
Fracture analysis of Hatten intrusion in Isfjorden, Svalbard	Tectonic reconstruction of the Yermak Plateau and Sophia Basin, NNW of Svalbard	Fault-magma interactions: investigating the influence of faults on magma emplacement on Spitsbergen and Edgeøya
HALIP and its possible impact on Mesozoic climate: modeling data for Svalbard	The Late Mesozoic to Early Cenozoic plate-tectonic evolution of the Greenland-Barents Sea shear margin	Geochemical signatures of HALIP volcanism in sedimentary record
Modelling the Eurekan deformation in the Arctic, an integration of geophysical and geomorphological observations in Gplates	Petrophysical evaluation of intrusions and associated contact metamorphic zones	Tectonic Evolution of the Barents Sea Margin: Fitting the Puzzle
Paleocurrent, stratigraphic analyses, and the detrital zircon record of the Devonian strata in the Arctic region	Gas generation in contact metamorphic aureoles: Sills and stacked Sills	Modeling gas generation in contact metamorphic aureoles of the Botneheia stacked sill intrusions
The impact of contact aureoles on seismic imaging: A central Spitsbergen example	Deep-time paleoclimate in the arctic: Proxy response at the Permian-Triassic boundary.	Metallic mineral potential of selected High Arctic Large Igneous Provinces (HALIP) in circum-Arctic
Comparison of two enigmatic suture zones in the Arctic: the South Anyui Suture and the Caledonian suture.	HALIP signal in the circum-Arctic stratigraphic record	Analysis of Digital Outcrop Models of the West Spitsbergen Fold and Thrust Belt
Trigger of the Permian-Triassic Mass Extinction: Impact or Volcanism?	Svalbard's drift through geological time and its link to paleoclimate	Fracture mapping of the Hyperittfossen digital outcrop model to constrain the paleo-stress field and tectonic history of Svalbard
Geochronology and Geochemistry of HALIP: clue to its origin. A review	Geodynamic Significance of Earthquakes in Svalbard	Syn-magmatic crater formation in the Arctic western Nansen Basin
The PETM signal in the Frysjaodden Fm. on Svalbard	Mineral Deposits of Svalbard	Crustal thickness evolution during North Atlantic rifting
	Geothermal potential of Svalbard, regarding	Burial history of Paleogene sediments

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	the Arctic Canada setting.	on Svalbard: paleotemperature implications of the Paleocene-Eocene Thermal Maximum in the Arctic
	Revealing Svalbard's basement using recently acquired gravity data	

6 Student perspectives

The international approach that is needed for Arctic research was reflected in the participants of the course. Over the course of the years, students from educational institutions in 11 different countries (Table 12), and from all inhabited continents, have enrolled in the course.

To characterize the student experiences, we have designed a questionnaire about the course and the NOR-R-AM project. Students who have enrolled in the course were invited to complete anonymous questionnaire about their experiences. Students were informed that the questionnaire was a part of a research project, and that their participation was voluntary and anonymous. Students provided informed consent to participate in the project before beginning the questionnaire. The questionnaire was sent to all course participants from 2018-2023 for completion in February 2024. 27 of the 57 invitees (47%) responded. In addition, four graduate students with significant NOR-R-AM involvement (i.e. active participation in at least three NOR-R-AM activities) were invited to provide discussion of the course based on their involvement and perspectives. These graduate students are co-investigators and co-authors in this project.

6.1 Student experiences questionnaire

Figure 8 summarizes the quantitative student experiences. The response group covers all of the four years when the course was run (2018-2023), with 55% of respondents being MSc students and 63% of the respondents never having been above the Arctic circle (Figure 8A). There is, ~~as usual,~~ a mix of students choosing the course based on the learning objectives and the course being held at UNIS. Notably, the vast majority (82%) of the respondents did not take a course on Arctic geology in the past. The student background was varied, including a mix of geologists, geophysicists and economic geologists (Table 3).

The course received largely positive feedback on the number and scientific diversity of guest lecturers, and the balance between field work, lectures, and seminars (Figure 8B). The course contributed to improving the familiarity of Arctic field conditions of the respondents, and an understanding of Arctic geology (Figure 8B). Approximately half of the respondents still contribute to the Arctic research community.

Table 3 lists a selection of responses to the more open questions. Practical skills and knowledge learned during the course include both geoscientific concepts but also the active use of different software, especially GPlates. Similarly, the biggest improvement experienced by the respondents was not just understanding geoscientific topics (with Arctic geology the key improvement for many) but also data integration, software skills and the development of independent research projects. The teaching methods were well received and the multidisciplinary, one-on-one supervision of research projects and active learning mentioned by several students. The final student comments indicate suggestions for improvement (such as more fieldwork and focus on single software) but also demonstrate the non-academic impact of the course for instance on networking and the student's personal development and networking.

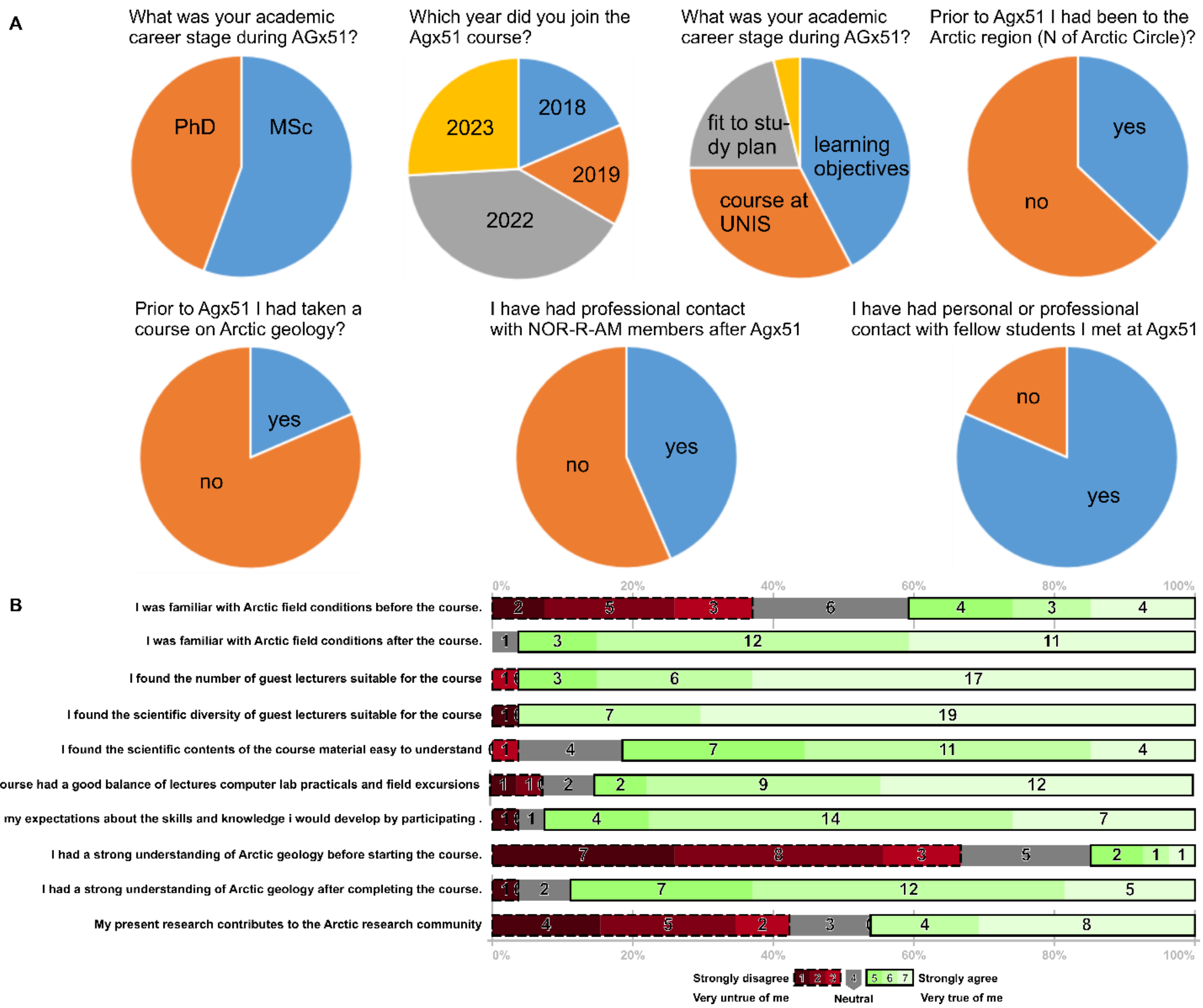

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Figure 8: Summary of the anonymous questionnaire circulated to past students of AGx51. 27 of 57 students responded. A) Background of respondents (in terms of career stage, year, previous background) and post-course interaction with fellow students and the NOR-R-AM scientific team. B) Responses to likert-scale questions on the student background and perspectives on various aspects of the course. Likert-scale plots generated using Maurer (2024).

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Table 3: Selected responses from text-based questions on the anonymous questionnaire.

Major field of study	Sedimentology, Structural geology, Glaciology, Geophysics, Geodesy, Data-analysis, Engineering Geology, Hydrogeology, Tectonics, Seismology, Petrology, Geohazards, Geodynamics, Paleomagnetism, Higher education in geosciences, Isotope geochemistry, Geomorphology, Volcanology, Geochronology, Economic geology
What are the particular practical skills or knowledge you have acquired during AGx51?	• an interplay between things we normally learn in single courses • As a non-geology student, i think the most important skill/knowledge i took with me home, was the idea of the overall picture of the geological history of a region, to further understand the "very" different fields that I'm working with in my normal study/work • a better understanding of scales (related to • tectonic structures) • Short paper writing with a deadline • Working with plate reconstruction tools • doing field work in the arctic, driving a snowmobile, 3D tectonic modeling, working with svalbox models, writing a report • build 3D outcrop models • work with a big range of arctic datasets and software like: Gplates, Petrel, Svalbox, VRSvalbard, Lime, Metashape and digital field notebooks. • Creating plate tectonic reconstructions in GPlates and adding own data to it. • Geological background of the Arctic region • Arctic field safety • Improved understanding of LIPs, sill and dyke emplacement • Networking
Can you provide one fact that you have learned during AGx51?	• There are several ways to define a Large Igneous Province • HALIP was a tectonomagmatic event present in the entire Arctic region • Fold-and-thrust belts have different parts with different structural expressions • Uplift shaping the paleogeography • I learned that you can capture stunning and accurate surface models with ordinary drones paired with the right software in order to visualize geological relationships for later use in research and education (virtual field trips) • Fish fossils could be found in the Old Red Devonian Sandstones of Svalbard. • The Gakkel Ridge is the slowest spreading center in the world, has focused magmatism, and no transform faults • The burial history of the Central Tertiary Basin • Arctic geological research is amazing!
What was the biggest improvement in your knowledge and skills that you attribute to participating in the course?	• My understanding of the geological history within the arctic area was much improved greater understanding of how the field of geology works • Field excursions developed skills in interpretating outcrops and own topic during the course enhanced information searching and writing skills. • The conception, planning and execution of the research article while incorporating new software and geological background knowledge. • better understanding of Arctic volcanism and paleo-environment • geological English, in particular, writing and presentation skills • Gplates and the importance of integrating datasets • Creating plate tectonic reconstructions in GPlates • Broader knowledge of geodynamics in general • better understanding of geochemistry • Interesting topic about the use of scientific colouration, that I use today.
How would	• It was less guided than in other courses I had, which was often positive (learn to figure out a lot by myself)

you describe the teaching methods in AGx51? And if relevant, how did they differ in terms of teaching methods to other courses you have taken.	• There was emphasis on the student to do some background reading and self-analysis (of literature or data). • The teaching methods were suitable for a small and focussed group with an emphasis on individual progress I was not familiar with compared to the lectures/ courses at my home-university. • For me the teaching method was unique as we got lectures from so many different experts in their own respective fields in such a short period of time. While at times it was a lot of information to progress, the final research project with one of the lecturers allowed you to go more into depth about a specific topic which especially sparked your interest, not something you were necessarily familiar with. • I really appreciate field work combined with working in class before and after about what we saw. Having passionate guest teachers was really inspiring. • Active Learning - hands on activities, core shack visits. • Geology-style manuscript and presentation doing our own research. • I liked the teaching methods. However, I did feel like we only had a small amount of time for our own projects. • Many lectures had a more relaxed/informal structure than lectures I have had elsewhere. • Very multidisciplinary and practical. Way more practical and one on one supervision compared to other courses.
Are there any other comments not covered about that you would like to make in relation to the AGx51 course?	• It was a very good opportunity to see how studying can be different. It was also somehow helpful to me to decide if I want to do a PhD (I got to know PhD-student much better than in normal courses and they could share their experience). I really liked meeting students from other universities and compare our experiences. • I think keeping future classes as small as possible is key for a good learning/interaction atmosphere. • I would have appreciated to focus on working with just one computer program, to get a good introduction. • I wish there were more fieldtrips! I know the logistics are hard but we went all the way there I wish I had seen more geology in-situ. Other than that, I look back on the course extremely fondly and I learned a lot. • I am so glad I participated in that course! • Those 6 weeks are in the top 3 of the best 6 weeks of my life and I'd like to thank everyone who contributed to this course and in making UNIS such a nice place in general.

6.2 Collective and individual student experiences

We (AS, FA, JJ, RKH) have each been involved in the AG-x51 course and the NOR-R-AM project at different stages of our research careers. We all participated in the course either as enrolled students during our MSc or PhD, and/or have assisted as polar bear guards. These perspectives allow us to collectively reflect on the course and the resulting opportunities that came from it.

The course was taught by members of the NOR-R-AM project, who are leading experts within their fields. This not only allowed us to learn about Arctic volcanism and tectonics from scientists with personal experience working in this region, but also gave us the opportunity to build professional relationships. This was made possible by utilizing the extensive time spent with our international peers and instructors during the course, including during lectures, practical sessions, research projects, fieldwork and social activities. This networking has led to many continuing personal development opportunities. To mention just a few of the opportunities, the course had profound implications on our career by collaborating with NOR-R-AM partners on our Master and PhD theses and even including some as official co-supervisors. Some of us were also able to join other NOR-R-AM courses, such as the geochronology workshop in Austin, Texas, or the field trip to Alaska (Table 4).

Moreover, NOR-R-AM was able to provide travel and analysis grants to accomplish the goals of the collaborations beyond those of the course. An overview of how the course functioned as a stepping-stone for further involvement in the NOR-R-AM program and what impact this had on our individual career paths is illustrated by Figure 9.

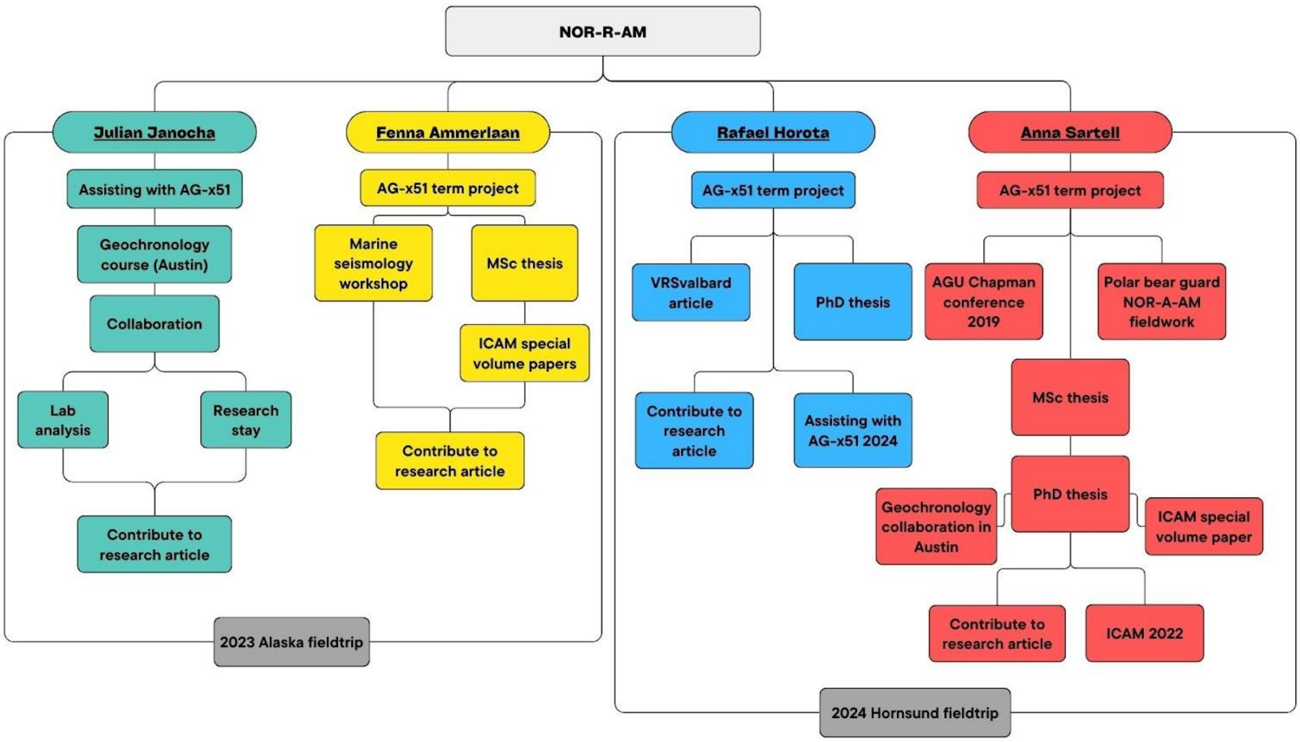

Figure 9: Summary flow chart of the involvement of four selected students in the NOR-R-AM project, including the UNIS course and additional activities.

6.2.1 Anna Sartell

I took the AG-x51 course as a master student in summer 2019. The teaching comprised lectures, practical sessions, field days, and the term project. For me as a student, the course promoted active learning and a hands-on approach to the topics taught. The learning went beyond memorizing literature and rather we learned how to use the knowledge we gained. The clear focus on practical learning throughout AG-x51 made this course very different to the rest of my education experience, in a positive sense. The highlight of the course itself was the opportunity to work closely with one of the lecturers on our term project, to expand further on what we had learned. Looking back, the biggest highlight has been the network that I gained from the course, which led to both my MSc and PhD theses being based on the topics of this course, the HALIP.

6.2.2 Fenna Ammerlaan

In autumn 2022 I was a Master student of the AG-x51 course. For me, the teaching approach of the different modules created a motivating environment as you recognized that you were being taught by experts in their respective fields. I believe this increased the effectiveness of the knowledge transfer, even though the number of teaching staff involved sometimes resulted in some overlap between the lectures. My personal highlight was the fieldwork conducted. Integrating what can be abstract geological concepts with physical observations helps to fully understand the material taught in class. This course was unique for me due to the international environment, diversity in student and lecturer backgrounds, intensity of the course and the fieldwork. Combining this with the remoteness of Svalbard, it felt like being part of a small community rather than just attending a course.

6.2.3 Rafael Horota

I was involved with the AG-x51 course both as a student (in autumn 2022) and polar bear guard (in spring 2023) during my PhD in higher education research. My involvement was motivated by the chance to gain firsthand experience from leading experts in Arctic volcanism and tectonics, and to apply cutting-edge technology like drone data collection in the context of geological Arctic field teaching. The teaching approach of the course, integrating lectures, practical sessions, research projects, fieldwork, social activities, had positively impacted me as a student. A personal highlight was the possibility to collect drone imagery, which was instrumental for my research, and because it supported fieldwork. This experience, coupled with collaborations established through the course, has been invaluable for my professional and academic growth. Compared to other courses, the AG-x51 course stood out due to its hands-on approach, and its fostering of international networks. The course’s blend of traditional academic learning with innovative research methods and technology application provided a richer, more engaging learning environment than I had experienced elsewhere.

6.2.4 Julian Janocha

I have never participated as a student in the AG-x51 course, but I have been helping with the organization of social events and as a polar bear guard in the summer of 2018. This was my first contact with the NOR-R-AM project. In the autumn of 2019, I had the chance to participate in the geochronology short course organized at the University of Texas at Austin. This event was one of the most influential in my research career. Learning about detrital zircon provenance and its applications I was inspired to include this in my PhD project which I started the following summer. This inspiration led to a three-month long research stay at the University of Texas at Austin in the winter of 2022 during which I accomplished a detrital zircon provenance analysis for my PhD project. The financial contributions by NOR-R-AM for both analysis and travel costs was essential for the success of this research stay. Overall NOR-R-AM has had a large influence on my professional career by offering courses, building a professional network and by providing financial support for collaborations.

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7 Discussion

7.1 Spatio-temporal perspective on Arctic evolution: teaching across country boundaries

Although our understanding of the geologic evolution of the Arctic is aided by geophysical surveys within the Arctic Ocean, we largely base our comprehension of this region on studies concerning the geology of the surrounding landmasses. Hence, within the Arctic, arguably more than anywhere else on earth, there is a considerable need for cross-country research and teaching collaboration to get a more complete picture of the region's geologic evolution. This becomes even more apparent as we travel further back in time. For instance, our rather incomplete understanding of the opening of the Amerasian Basin in the Mesozoic requires correlation of tectonic and magmatic events and geologic units from the Canadian Arctic, Alaska, and northeastern Siberia (Shephard et al., 2013). As we get even further back in time, such as understanding the extent of the late Proterozoic/ early Paleozoic Timanian Orogen, we require comprehension of sparse geologic evidence of this mountain building event identified in locations such as Siberia, Scandinavia, North America, and numerous Arctic archipelagos (e.g., Svalbard, New Siberian Islands, Severnaya Zemlya; e.g., Gee et al., 2006). So, the further we delve back in time, the more uncertain the reconstruction of the Arctic's geologic evolution becomes and the more a spatio-temporal perspective on Arctic evolution demands an interdisciplinary and collaborative effort that transcends national boundaries. The NOR-R-AM collaborative project has aimed to address this through providing numerous international educational opportunities (e.g., the course described in this contribution) in order to bring researchers and students from various Arctic countries together, and to gain perspective on the geology of the Arctic regions from other countries.

In addition, the vast and remote landscapes of the Arctic, coupled with harsh climatic conditions, have limited the accessibility and comprehensive mapping of geological features and acquisition of field data. The scarcity of geoscience data highlights two needs within the Arctic community: 1) cross-country collaboration to generate a reliable database to store this patchwork of data and 2) availability of testable geodynamic models that take into account data that transcends international boundaries. Cross-country initiatives, such as the NOR-R-AM project, are necessary r to bring together researchers from various nations to pool their expertise and resources. This collaborative approach recognizes that no single country possesses the entirety of the puzzle; instead, a mosaic of insights from different perspectives is required to construct a comprehensive narrative of the Arctic's geologic evolution.

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7.2 Lessons learned: data, tools, software, workflows

From the onset we have designed the course with focus on active, hands-on learning at the expense of frontal lecture-based education. A culmination of this are the student research projects where adequate (but not infinite) time is allocated to test a scientific hypothesis using the provided data and skills sets.

To make the course as authentic as possible, we teach and integrate a broad range of softwares and tools (Table 4). Obviously there is no time within a 6-week course period to go in depth in all of these, but the entire class is introduced to all the tools and given a demonstration. For data mining, GPlates and SILLi these are also linked to hands-on exercises for the entire class. For smaller student groups that use a specific software during their term projects additional hands-on sessions are organised. In addition, we used a pre-course questionnaire to identify the strengths of individual students (for instance significant experience in GPlates) who acted as additional tutors in the hands-on sessions to assist their peers.

With such diverse software we have devised pre-loaded projects in Petrel and GPlates softwares (Figure 10), with the data packages available to anyone as part of the supplementary material (Senger and Shephard, 2023). Petrel is largely used to spatially integrate surface (terrain models, bathymetry, geological, topographical and satellite maps) with subsurface (borehole and geophysical data plus geomodels). The thematic data set provided for the AGx51 builds on the ongoing Svalbox project. The key benefit of such direct integration is to spend less time on data loading and more time on the scientific benefits of data integration, for instance in the AGx51 student projects. The integration of multi-physical data, for instance aerogephysics with geology, also facilitates joint interpretation. Finally, the provision of curated (and regularly updated) databases as we do for the AGx51 course is even more important in the Arctic where data are often fragmentary and acquired sparsely over a large area.

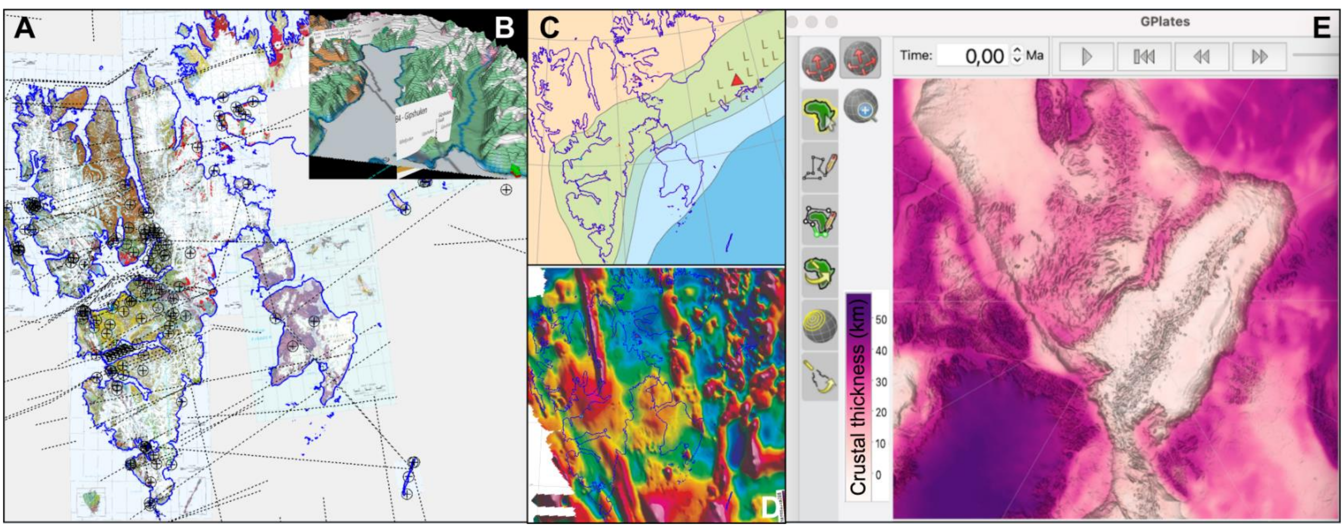

Figure 10: Synthesis of the spatial and temporal elements provided in the supplementary material (Senger and Shephard, 2023). A) Interactive geological map of Svalbard also showing the location of published profiles (dashed lines; includes both seismic profiles and geological cross-sections) and location of boreholes and selected published sedimentary logs from outcrops. B) Zoom-in of a 3D view of Billefjorden where a digital terrain model was draped with a geological map and two profiles across the Billefjorden Fault Zone are co-visualized. C) Published paleogeographic map (Dallmann (2015) from the Barremian (125 Ma), overlain with the extent of HALIP magmatism onshore Svalbard. D) Published magnetic anomaly map (Dallmann 2015). E) Example of crustal thickness map at present day as illustrated in GPlates. The software also facilitates the digital visualisation of plate tectonic reconstructions through geological time.

Table 4: Tools, software and key data sets used in the course include a mix of free and open-software and proprietary software. All software programs or tools were accessible for all of the students (whether in computer lab or personal laptop) and were used for the individual student research projects.

Software/tool	Course module	Reference or link
GPlates	Plate tectonics	https://www.gplates.org/ Müller et al. (2018)
SubMachine	Mantle structure	http://www.earth.ox.ac.uk/~smachine Hosseini et al. (2018)
Svalbox online	Data mining, Svalbard geology	www.svalbox.no/map Betlem et al. (2023) and Senger et al. (2021b)
Svalbox Petrel	Data mining, Svalbard geology	Horota et al. (2023) and Senger et al. (2022)
VRSvalbard	Data mining, Svalbard geology	www.vrsvalbard.com/map Horota et al. (2024)
Online map resources	Data mining, Svalbard geology	
LIME	Digital geology	Buckley et al. (2019)
SILLi	Volcanism and environmental impacts	Iyer et al. (2018)
Digital field notebook	Field work	Senger and Nordmo (2021)
Digital data package	GPlates and Petrel pre-loaded projects	Senger and Shephard (2023)

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7.3 Transforming geoscience education through hands-on digital tools

The main motivation of exposing the students to such a wide range of software within a short time frame is to appreciate that geoscience is undergoing a digital transformation (Bouziat et al., 2020; Gunderson et al., 2020). Mccaffrey et al. (2005) early on recognized that affordable digital technologies will revolutionize how field geology is conducted. Ruggedized tablets, as described from the Svalbard environment by Senger and Nordmo (2021) or Lidar-equipped iPhones (Tavani et al., 2022) drone-based imagery have led to the widespread adoption of digital outcrop modelling (Betlem et al., 2023). Geology has traditionally been an observation-focussed domain, with a focus on measuring nature at various scales, recording mostly qualitative data in the field. Through digitization, we bring quantitative and repeatable analyses into geology, for instance through active use of digital outcrop models or time-lapse digital plate tectonic reconstructions. Such efforts are necessary not just to gain a better understanding of Earth's evolution but will also have the added benefit of recruiting students to the geosciences and bridging the gap between geoscientists and data scientists.

The complex spatial-temporal tectono-magmatic evolution of Svalbard imposes logistical challenges to exemplify geological concepts in the field within the framework of the AG-x51 course. However, modern technology and digital tools provide innovative solutions to overcome these obstacles. Geospatial data and GIS are essential for creating detailed maps of the region, facilitating the teaching of concepts like tectonic evolution and volcanic processes. 3D modeling and visualization tools allow for the creation of immersive models that aid in understanding complex geological structures by supporting 3D thinking. Remote sensing technologies, such as drones and satellites, provide real-time data and images, enabling students to change the observer's perspective when analyzing large scale geology. Digital workflows and analytical tools streamline data analysis, while online collaboration platforms enhance collective learning experiences. Virtual field trips offer a safe and accessible way for students to explore Svalbard's geological features, fostering a deeper understanding of the region's unique geology. In essence, the integration of these digital tools and workflows empowers students to engage in hands-on learning, regardless of the remote and challenging environment of Svalbard.

In the unforgiving Arctic field sites such digital tools are almost a must to overcome the various challenges of field teaching at Svalbard (Senger et al., 2021a). However, learnings from the Arctic, be they technological, pedagogical or both, can also be adapted at more temperate latitudes to improve accessibility (Whitmeyer et al., 2020; Atchison and Libarkin, 2013). We are also strong proponents that active and targeted digital geoscience tool usage in both education and outreach can significantly improve the diversity challenge faced by the geosciences (Hall et al., 2022).

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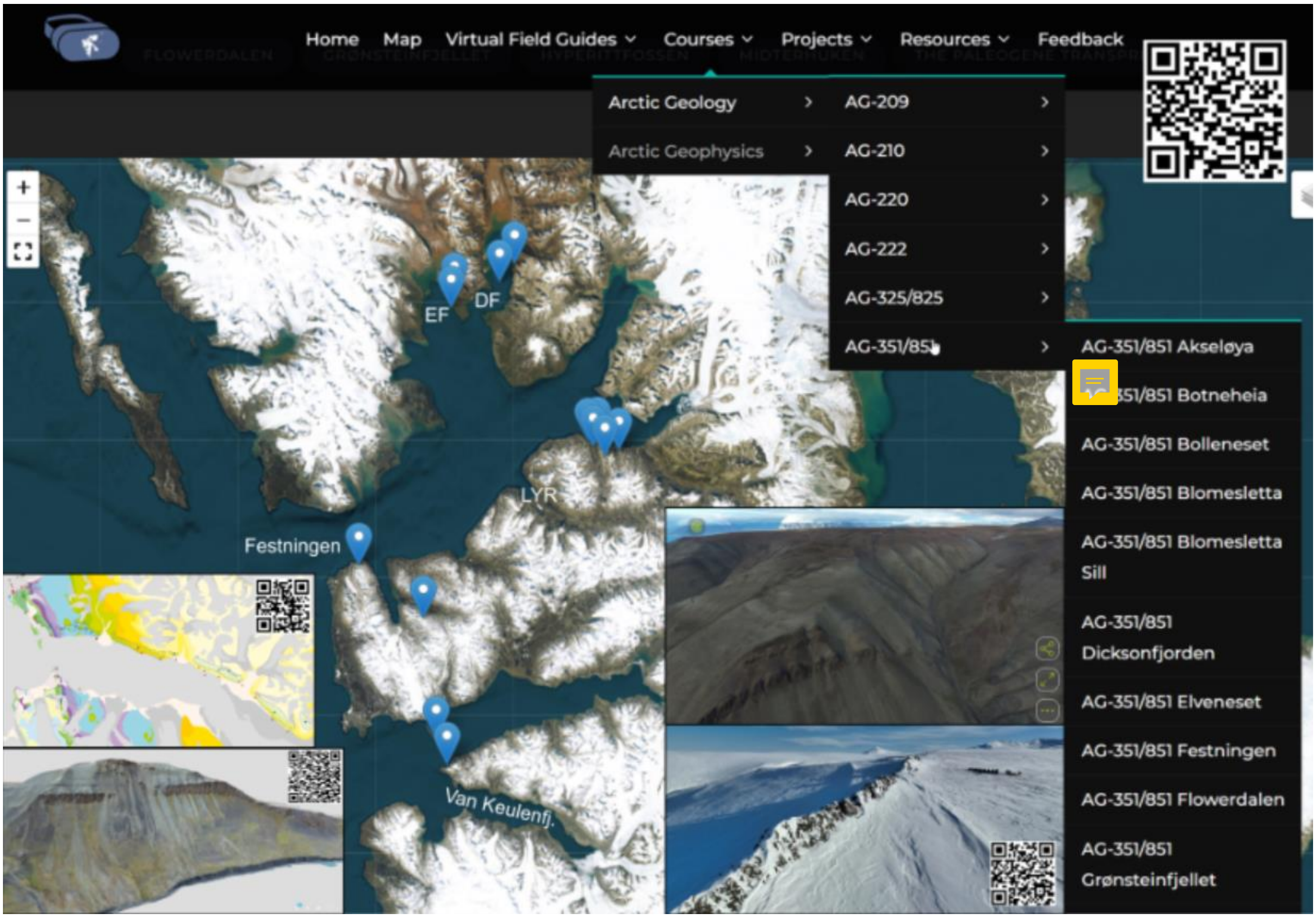

Figure 11: Synthesis of data systematically acquired as part of the AG351/851 course and openly available on VRSvalbard (https://vrsvalbard.com/ag-351-851/; access via main QR code). The geological inset map illustrates the photosphere and digital outcrop model coverage in Van Keulenfjorden where the Central Basin infill is well exposed. The interactive map at https://www.svalbox.no/map is accessible with the QR code. The low inset image illustrates a digital outcrop model of the 310 m high mountain Grønsteinfjellet visited during fieldwork in October 2022 (https://sketchfab.com/3d-models/grnsteinfjellet-7185d44b49d74a9daad35f438d52cf2a). The Botneheia locality as visited in April 2023 provides an excellent exposure of a HALIP dyke. Photospheres taken in summer complement the winter snow-covered conditions and are freely available through https://vrsvalbard.com/botneheia/.

7.4 Beyond the AG-x51 course: NOR-R-AM educational activities

In this contribution we have focussed on the AG-x51 NOR-R-AM flagship course that also continues beyond the project period, however, Table 5 lists other educational and outreach activities undertaken as part of the NOR-R-AM project. The geographic and thematic diversity of these events testifies to the international and multi-disciplinary nature of the NOR-R-AM project. Two workshops are further detailed below.

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The 2023 Marine Seismology Workshop was organized jointly by the Canadian National Facility for Seismological Investigations (https://nfsi.ca/), Dalhousie University (Halifax, Canada) and the University of Ottawa, and invited participation from various international graduate training programs including NOR-R-AM. In total, 40 participants from 15 different institutions across 6 different countries attended the workshop, including 20 graduate students. The workshop program featured foundations in theoretical and applied seismology, hands-on practical exercises on the computer, a tour of the facility and demonstration of instruments and ancillary gear, a deployment of broadband ocean-bottom seismic stations offshore Halifax, a survey proposal planning competition, and research seminars by invited guest speakers. This activity was an integral part of the NOR-R-AM WP3 on Arctic Seismicity and Deep Interior and combined seismological field training with Arctic tectonic discussions and challenges associated with survey planning.

A one-off geochronology workshop was held 4-9 November 2019 at the University of Texas in Austin. The course provided an introductory understanding of geochronology and thermochronology with in-depth theoretic and practical exposure to U-Pb and (U-Th)/He geo- and thermochronometry. The main course objective was to introduce students to the methodologies, analytics, data reduction and interpretation in U-Pb geochronology and (U-Th)/thermochronology. The course covered theoretical aspects of U-Pb and (U-Th)/He dating, practical aspects including sampling strategies, mineral separation and preparation. Students were exposed to hands-on analytical training in the laboratory using samples collected in Svalbard from grain to data. Besides theoretic and practical analytical training, the students also learned how to interpret detrital zircon U-Pb data for paleogeography and tectonics restoration with emphasis on the Paleozoic and Mesozoic Arctic regions. For this purpose, students used zircon databases and GPlates software and learned how DZ U-Pb and He data could be used for improving plate tectonic models and reconstructions.

Table 5: Overview of NORRAM educational and outreach activities. The location of the activities is plotted in Figure 1.

Event and location	Date	Comments
Alaska transect field trip	25 August-5 September 2023	ca. 25 NOR-[R-]AM participants and guests participated in a 2 week field excursion from the south to the north of Alaska, from Homer to Galbraith Lake. Such a transect took the participants across a number the vast number of accreted and deformed terranes of Alaska. The group were also treated to sites related to permafrost, past glaciations, the Trans-Alaska pipeline, and local culture and history.
Maine Seismology Workshop, Dalhousie University in Halifax, Canada.	May 22-26 2023	ca. 40 participants, 4 of which from NOR-R-AM, attended a 5-day workshop to get training in marine seismology, including passive and controlled source methods, ocean-bottom seismic instrumentation, deployment/recovery and location on the seafloor, data collection, data processing, and survey proposal planning.
Svalclime workshop,	18-22 Oct 2022	Magellan+ workshop on scientific drilling in Svalbard for deep-time

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UNIS, Longyearbyen		paleoclimate, see (Senger et al., 2023) for details
International Conference on Arctic Margins ICAM9 - Ottawa Canada	13-15th June 2022	Numerous NOR-R-AM members involved in organization and presentations at the 9th International Conference on Arctic Margins
Fagradalsfjall eruption in Iceland webinar, online	June 10th 2021	The American Geosciences Union (AGU) and NOR-R-AM hosted a webinar which saw over 300 live attendees tune-in. For more information please see the link below. A recording of the webinar is available at https://youtu.be/O5-ALyvDem4
Geochronology short course at University of Texas at Austin, USA	3-10 November 2019	Introductory understanding geochronology and thermochronology with in-depth theoretic and practical exposure to U-Pb and (U-Th)/He geo- and thermochronometry. .
EGU General Assembly sessions	19-30th May 2021 4-8th May 2020 7–12 April 2019 8–13 April 2018	Arctic geology specific sessions led by NOR-R-AM participants; “The Arctic connection – plate tectonics, mantle dynamics and paleogeography serving paleo-climate models and modern jurisdiction” or “The Arctic connection – geodynamic, geologic and oceanographic development of the Arctic.”
AGU Chapman conference, Selfoss, Iceland	13-18 October 2019	“Large-scale volcanism in the Arctic: The role of the mantle and tectonics” conference was of the major outcomes NOR-R-AM, bringing together 100 international researchers from wide-ranging backgrounds and career stages. Iceland (town of Selfoss) was chosen as a half-way meeting point for the European and North American based communities.
AGU Fall Meeting session	10-14 December 2018	Arctic geology specific sessions led by NOR-R-AM participants; “The Arctic Connection: investigating the tectonic evolution of the Circum-Arctic” (Session ID: 49611 Session Title: T046).”
Wilson cycle fieldtrip	August 2019	Journey from eastern to western Norway through the Norwegian Caledonides, to look at rocks that tell the story of the Wilson Cycle (The formation of wide continental margins, oceanic crust, island arcs and the final continental collision and mountain building). Series of 4 documentaries released on YouTube. https://www.mn.uio.no/ceed/english/about/blog/2022/the-wilson-cycle-in-4-stages.html
Field trip to Eastern Siberia	August 2018	6 NOR-R-AM participants participated in a 3 week field excursion in NE Siberia. They crossed the Verkhoyansk fold belt from west to east, sampled Mesoproterozoic to Cretaceous strata for isotopic study, did structural investigations.

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8 Conclusion

In this contribution we have outlined an international collaboration project, 'NOR-R-AM' ("Changes at the Top of the World through Volcanism and Plate Tectonics") and specifically focussed on a graduate course on "Arctic Tectonics and Volcanism" held annually at the University Centre in Svalbard since 2018. We conclude that:

- Political and discipline boundaries must be set aside to comprehend the geological evolution of the Arctic
- Teaching Arctic geology requires provision of circum-Arctic data spanning both spatial (lateral and vertical) and temporal (i.e. geological evolution) scales.
- The multi-disciplinary course "Arctic Tectonics and Volcanism" exposes the students to various tools and methods in order to decipher one particular aspect of Arctic geology through an individual research project.
- Four NORRAM students provided specific examples into how the course and the NORRAM project impacted their respective careers, primarily through networking opportunities, grants and supervision of research projects.
- We provide three open data sets that may facilitate circum-Arctic teaching beyond UNIS.

Author contributions

KS - Conceptualization, Investigation, Resources, Data Curation, Writing - Original Draft, Visualization, Supervision, Project administration, Funding acquisition

GS - Investigation, Resources, Data Curation, Writing - Original Draft, Visualization, Supervision, Project administration

FA - Writing - Original Draft

OA - Writing - Original Draft

PA - Writing - Review and Editing, Supervision

BC - Writing - Review and Editing

VE - Writing - Review and Editing

JIF - Writing - Review and Editing

SAG - Writing - Review and Editing

RKH - Writing - Review and Editing, Visualization

KI - Writing - Original Draft

JJ - Writing - Original Draft

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MTJ - Writing - Original Draft

MO - Writing - Original Draft

AM - Writing - Review and Editing

ASA - Writing - Original Draft

ASC - Writing - Review and Editing

DS - Writing - Original Draft

MVK – Writing – Review and Editing, Supervision

CG - Writing - Original Draft, Visualization, Supervision, Project administration, Funding acquisition

Competing interests

The authors declare that they have no conflict of interest.

Ethical statement

While the course focussed on a geopolitically and controversy-prone area, we do not foresee any ethical issues with this project as it pertains to students' experiences in a course. The questionnaire, which was both anonymous and voluntary, was developed in line with the Norwegian National Ethics Committee's Guidelines for Research Ethics in the Social Sciences and Humanities (which is the most relevant set of ethical guidelines for teaching related research projects). Further, the project was reviewed by UNIS' internal ethical committee. No specific permission from a research ethics board is required for this kind of research in Norway and thus could not be sought. Four graduate students with significant NOR-R-AM involvement were invited as co-authors to this contribution based on their significant involvement in several activities.

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Data availability

The educational material associated with the course (i.e. Petrel and GPlates data packages) is freely available from the Zenodo repository (Senger & Shephard 2023). Other data are available on request by contacting the corresponding author.

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